Measurement of Capillary Refill Time (CRT) in Healthy Subjects using a Robotic Hand

Measurement of Capillary Refill Time (CRT) in Healthy Subjects using a Robotic Hand

Anonymous CVPR submission

Paper ID 14

Abstract

A human's Capillary Refill Time (CRT) is a key indicator of their current health status. Being able to accurately assess a human's cardiovascular system peripherally by assessing their CRT in an emergency or search and rescue situation could, in critical scenarios, mean the difference between life and death. This paper presents a novel algorithm that enables a Shadow Robot Hand equipped with BioTAC biomimetic tactile fingertip sensors and a red, green, blue (RGB) camera to measure the CRT of humans by making contact with their forehead, regardless of their skin tone. The method presented replicates, to some extent, the methods carried out by medical professionals when measuring CRT and could be used to equip a first responder robot. Furthermore, the algorithms determine whether a person has a healthy cardiovascular system or whether the blood supply has been cut off from the skin indicating various issues such as shock or severe dehydration. The method presented in this work allows for a more accurate measurement of CRT than that of a medical professional.

1. Introduction

When assessing a person's condition in an emergency or rescue situation, responsiveness, Respiratory Rate (RR), heart rate Beats Per Minute (BPM), blood circulation and assessment of their cardiovascular system are all critical measures of the subject's health. One method of assessing the cardiovascular system peripherally is by assessing the CRT. Although it would be preferable to have more detail, such as the blood pressure reading of the human to assess their cardiovascular system, it is not always possible to get these readings, especially in cases of emergency. The CRT is the time taken for the colour to restore in an external capillary bed following blanching caused by pressure being applied. The CRT can be measured by pressing on the fingernails, the soft tissue at the kneecap or forearm, the centre of the chest or the forehead [1]. To measure CRT from the human's forehead, it is necessary to press a finger into the centre of the forehead for approximately 5 seconds and then release it. When measured at the forehead, the normal time for CRT should be less than 2 seconds for an adult, up to 3 seconds for an infant or up to 4.5 seconds for an elderly person [2]. Therefore, if the skin returns to its normal colour within 0.5-4.5 seconds (depending on age, sex, temperature etc.) then it can be assumed that the cardiovascular system is performing normally. In the majority of cases it should be under 2 seconds for a healthy human [3]. If normal colour returns within the expected time period from the press, then the skin is getting a healthy supply of blood. If not, it could be a sign that the body has gone into shock [4], an indication of dehydration [5], decreased peripheral perfusion or that the blood supply has been cut off from the skin. The skin is the first organ from which the body cuts blood supply to in the event of severe harm or illness.

Having a robot equipped with the necessary intelligence and skills to read vital signs such as CRT, RR and BPM using tactile sensors will prove to be extremely beneficial. Reading a person's pulse is one common method of assessing their blood circulation. However high levels of skills and experience from medical personnel can be required to read and analyse the pulse. Measuring RR can be a very tricky procedure as it involves counting how many times the chest rises in one minute, which can be challenging when the patient is breathing weakly. To date methods and algorithms for the retrieval and calculation of pulse (BPM), the Pulse to Pulse Interval (PPI) (i.e. time between detected pulses) [6, 7], RR and the Breath to Breath Interval (BBI) (i.e. time between detected breaths) [7] have been developed. The purpose of this work is to ascertain if a robot hand equipped with sophisticated tactile sensors (biomimetic fingertips) is capable of accurately detecting and measuring CRT in the same manner as a human. Similar to a human fingertip, BioTAC biomimetic fingertips on the robot hand are capable of measuring vibration (representing texture), thermal conductivity, static temperature and force [8]. This paper describes a novel method which computes CRT by using the Shadow Robot Hand and a Bio-

TAC sensor to press against the subject's forehead with a safe, pre-calculated force for 5 seconds. Image processing techniques are used to determine how long it takes for their skin colour to return to normal, by using a micro 1000 Television Lines (TVL) camera and visual processing algorithms.

The remainder of this paper is organised as follows: Section 3 describes the data collection and the algorithm developed for measuring human CRT. Section 4 presents results for CRT calculations. Conclusions and plans for future work are in presented Section 5.

2. Background and Related Research

Although CRT is a critical clinical indicator of trauma and detection, digitised CRT techniques are not readily available or researched [9]. CRT is normally assessed by visual inspection at certain points around the body for example the chest, fingertip or forehead by a trained clinician; however, this method is prone to high inter-observer variability due to manual time measurement [10]. Even though there is evidence that the pressure and duration of contact on the forehead, chest or fingertip can significantly influence the measured CRT, currently pressure and duration are poorly standardised [11]. Furthermore, the assessment of CRT can be influenced by variability in environmental conditions such as lighting and temperature [12, 13].

An automated system involving a non-invasive adhesive sensor incorporating a pneumatic actuator, a battery operated datalogger unit containing a self contained pneumatic supply, a temperature sensor, a diffuse multi-wavelength reflectance measurement device and a PC was developed by Blaxter et al. to automatically measure CRT [14]. It was demonstrated that their method could repeatedly measure CRT in both adults and children. Furthermore, the authors measured the CRT of the subjects at different temperatures and proved that temperature has an influence on CRT measurement as stated by [12, 13]. Although the device could measure CRT, it is a specially made device and requires adhesion to the forehead of the subject which should be left there for continuous monitoring. Kviesis-Kipge et al. [15] developed a device to measure CRT from human fingertips using a photoplethysmography (PPG) contact probe operating in the blue region of spectrum. It was found that the colour of the fingernail did not always return to the colour it was prior to compression and therefore the algorithm could not repeatedly measure a subject's CRT. It was proposed that further work was required on the sensor to allow for greater accuracy in CRT measurement.

The work in [9] aims to address this variability by standardising the pressure placed on the finger when using a small portable device to assess CRT by analysing PPG recordings. They assess the use of their standardised rules on a paediatric dataset to validate 93 readings from fingertips and reliably detected invalid CRT readings, with a sensitivity rate of 98.4%. Invalid readings are caused by numerous issues such as low perfusion signals, insufficient pressure, and artefacts. Although a promising step towards a reliable digital method to validate CRT measurements, this approach is not capable of directly measuring CRT and requires the use of other algorithms. Shavit et al. [16] developed an image processing method to measure CRT from the fingertips of children with the aim of increasing the accuracy of diagnosing dehydration. A camera recorded the child's fingertip during the procedure and recorded the time it took for the colour of the finger nail to return to the colour it was before contact was made. The digital measurement of CRT, namely digitally measured capillary-refill time (DCRT) was compared to the CRTs measured by medical professional on the same children. Although it was found that the (DCRT) was more specific that that of the CRTs measured by the medical professionals the procedure still required an operator to apply pressure to the childrens fingernail, making it a semi automatic process. Due to this, and the requirement for the configuration of the camera, the authors felt that it is impractical for routine use in clinical settings in it's current design [16]. The device would also be unsuitable for emergency scenarios. Algorithms for use with a tactile sensor that are capable of accurately measuring CRT are not available to date. Such an algorithm could provide a "first response" service to a user or could be used to determine a human's health status in an emergency rescue scenario before risking further human life.

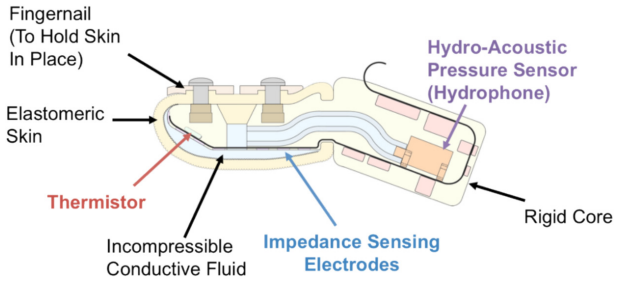
3. Methodology

This section provides details on the equipment used for the retrieval of CRT data, the data collection process and the algorithms used to determine the length of time taken for the subjects' skin tone to return to its normal colour, i.e. the subject's CRT.

3.1. Determination of CRT

The Shadow robot hand, made by the Shadow Robot Company, equipped with three BioTAC™ sensors from Syntouch® , as shown in Figure 1(a), together with a micro 1000 TVL camera, was used to collect vision data from the human subjects' foreheads. The Shadow robot hand has 21 degrees of freedom and has similar dexterity to a human hand [17] allowing it to mimic, to some extent, the actions required to measure CRT from a human's forehead. The BioTAC is a tactile sensor which is shaped like a human fingertip and is liquid filled, giving it similar compliance to a human fingertip [18, 19]. Like a human finger, it is capable of detecting a full range of cutaneous sensory information: forces, micro vibrations and temperature. Figure 1(b) shows a cross-sectional view of the BioTAC fingertip.

(a)

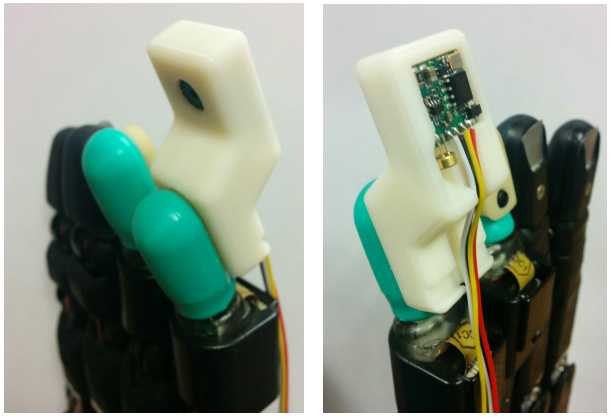


(b)

Figure 1. a) An image of The Shadow Robot Hand [20] with a RGB camera mounted; b) Cross Section View of BioTAC Fingertip Tactile Sensor [17]

As outlined in [6, 8, 18, 19] the BioTAC fingertip measures force applied across an array of 19 electrodes. It measures absolute temperature (the DC temperature, TDC) and thermal flow (the AC temperature, TAC), the rate at which heat is leaving the fingertip and transferring to what it is in contact with, and measures vibration. It outputs two different values, one is a DC pressure signal (PDC) which is the reading obtained after passing through a low pass filter and the other is an AC pressure signal (PAC) which has been passed through a band pass filter. In the case of using the BioTAC sensor with the Shadow Hand for determining CRT, the data from the force electrodes sensors are the only data utilised.

To establish if an accurate measurement of a human's capillary refill time can be calculated by analysing the change in skin colour as a result of a press action being carried out on the centre of the subject's forehead, the Shadow Hand was equipped with a camera. A customised camera mount that can clip securely onto the fingernail of a BioTAC fingertip was designed and built using a 3D printer. The customised camera mount can be seen in Figure 2. A small 1000 TVL camera was inserted into the mount and the video data was recorded on a PC by using a Universal Serial Bus (USB) video grabber.



(a) (b)

Figure 2. Images showing the customised camera mount on the Shadow Hand from (a) the front and (b) the rear.

3.2. Data Collection

Data collection involved the use of 12 healthy subjects. All subjects were male aged between 18-65 years who were in generally good health, had never been diagnosed with a heart or lung condition and had never had surgery on their heart or lungs. Due to the nature of the data recording during these experiments, no female subjects were recruited at this stage of the investigation. Ethical approval was granted by the research governance of Ulster University for all experiments carried out. An exclusion process was carried out for each subject prior to participation to ensure that they met the required criteria. Each non-excluded subject was fully briefed about the experiment and signed a consent form prior to participation. To ensure that the subject was in generally good health at the time of data collection, the researcher collected each subject's temperature using an ear thermometer with a new tip for each subject, following training on how to do so from a medical professional. The medical professional also oversaw the procedure and used a standard medical practice to measure each subject's CRT to verify if the subject had a CRT in the same category as determined by the artificial system approach presented (i.e. normal or prolonged). Each subject sat in a standard chair in front of the robot hand which was positioned very close to the subject's forehead. Data were collected at different times of the day, meaning ambient light could have changed slightly from subject to subject. When video recording commenced, the region of interest (approximately $12cm^2$) on the forehead was captured for 5 seconds before the first finger of the Shadow Hand, equipped with the small 1000 TVL camera, was pressed against the centre of the subject's forehead for 5 seconds with a constant force, small enough not to induce pain. The fingertip was

then moved back to its starting position and video data of the area of interest on the subject's forehead was captured for a further 10 seconds. The short time before the fingertip applied pressure enables the camera to auto focus and capture the subject's natural skin colour so that it is possible to identify when their skin returns to its natural colour. Based on advice from a medical professional, 10 seconds was considered sufficient recording time after pressure as a CRT of anything more than 10 seconds is normally an indication of subject death. An abnormal CRT (i.e. from 2-10 seconds) can be a sign of illness or that the body has gone into a state of shock. The applied force was measured using an ATI Nano17 6-axis Force/Torque (F/T) Sensor [21], when applied by a trained medical professional mimicking the same procedure. This procedure improves standardisation of the magnitude and duration of the force applied. The impedance values measured by the array of electrodes on the BioTAC sensor were used to ensure that a constant force, similar to that of a medical professional, was applied in each case. At no stage was the subject's entire face or body filmed or recorded. A medical professional was consulted to verify that the action was completely safe and non-intrusive. There was a soft emergency stop in place to stop the robot hand from applying too much pressure on the subject at any time and furthermore the power to the robot could be cut instantaneously in case of emergency, posing no risk to the subject at any time. This procedure was completed 3 times for each of the 12 subjects.

3.3. Image Analysis

Videos were recorded at a frame rate of 30 frames per second (fps). The videos were split into still frames using the FFmpeg [22] software and imported into MATLAB [23] where the remaining analysis was completed. Figure 3(a) shows an image of a subject's forehead taken immediately after the press and shows the skin to be pale due to the capillaries being compressed and emptied, while Figure 3(b) shows an image of the same subject's forehead as the capillaries begin to refill. This shows the skin to be much redder as it returns to its normal colour.

The red, green and blue histograms were retrieved for each image per subject and the mean value of each colour's histogram calculated. A plot of the mean value for each colour histogram across a sequence of frames from one recording is shown in Figure 4.

As red is the most significant colour to signify the refill of the capillaries, the red pixel value is extracted from each recording and used for further analysis to determine the CRT. A plot of the mean pixel value for red only is shown in Figure 5 where the labels 1,2,3, and 4 denote phases of change in the red pixel value.

Prior to contact with the forehead it is evident from Figure 5 that the average value of the red pixels is slightly

(a)

(b)

Figure 3. a) An image of a subject's forehead taken immediately after the press; b) An image of the same subject's forehead taken as the capillaries begin to refill

higher than the average value post contact, phases 1 and 4 respectively. This is to due to shadows cast by the fingertip being close to the forehead causing the image to be darker than normal. Upon release of the fingertip from the forehead, it is expected that there would be an immediate drop detected in the red pixel value as the contact area is initially still whiter than normal due to the blood flow being temporarily stopped in the affected capillaries during contact; this is evident in phase 2 of the graph in Figure 5. In a healthy human, it is expected for this to be rapidly followed by a rush of blood vessels to the area as the capillaries refill, resulting in a spike in the red pixel value, as witnessed in phase 3 of the graph Figure 5. The time from the instance that the skin regains blood flow (i.e. the beginning of phase 3) until the time it has settled at its original pigment (i.e. the beginning of phase 4) represents the CRT. Phase 4 in

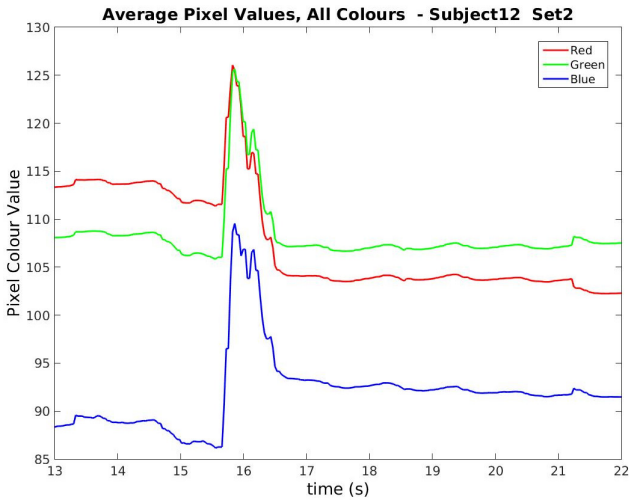


Figure 4. Graph showing the mean values of each histogram across a sequence of images

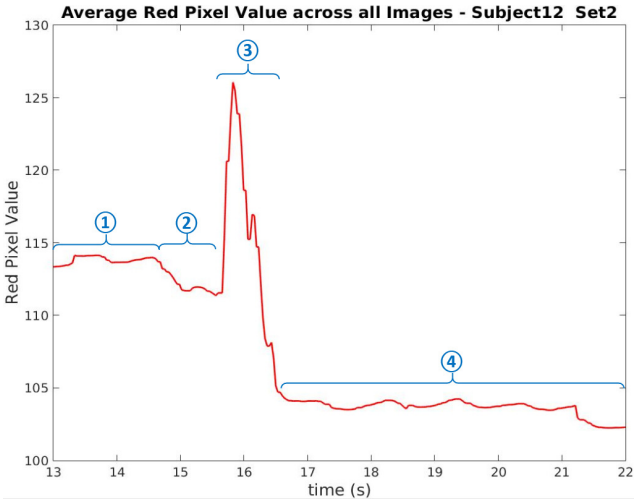


Figure 5. Graph showing the mean values of the red histogram across a sequence of images

Figure 5 shows that the skin appears to return to a steady colour where the red pixel value is lower than it was immediately before contact (in phase 1). This is due to the fact that the fingertip is now slightly further away from the forehead than it was when it was pressed against it, resulting in less shadows and ultimately a lighter colour being detected by the camera. Therefore, the exact time of transition from the drop in the red pixel value to the rise in the value of red pixels and the exact time when the skin settles, no longer changing colour, must be identified. Calculating the difference between these two times (i.e. the length of phase 3 in Figure 5) will result in an accurate measurement of CRT.

To identify the start and end times of the capillaries refilling, the graph is cropped to focus on the area surrounding the highest value of the red pixels. The time stamp of when the capillaries are being refilled (i.e. the highest peak) is calculated and the graph is cropped 5 seconds before and 10 seconds after to reduce the volume of data to analyse, hence increasing the efficiency of the algorithm. In order to identify the time stamp when the spike in red pixel values started and ended, it was necessary to analyse the gradient of the graph at each time stamp. A sliding window was used to calculate the moving gradient along the graph using Equation 1 and each gradient and its corresponding time stamp were stored in an array for further analysis:

$$m_t = \frac{r_t - r_{t-1}}{T_t - T_{t-1}} \tag{1}$$

where m_t is the gradient at time t, r_t and r_{t-1} are the red pixel values at time t and $t-1$ respectively, T_t and T_{t-1} are the times at t and $t-1$ respectively.

To disregard insignificant gradients caused by noise and identify significant gradients, a threshold was calculated for each dataset. The threshold for identifying significant positive gradients was set as the mean of the positive gradients and the mean of the negative gradients was used as the threshold for identifying significant negative gradients. To compensate for the change in the average value of the red pixel before and after the press on the forehead, an average of the highest and lowest values of the red pixel is calculated. This value is taken as the mid-line of the red pixel value and is shown by the green line in Figure 6. This mid-line was used as the baseline to demonstrate changes in gradient.

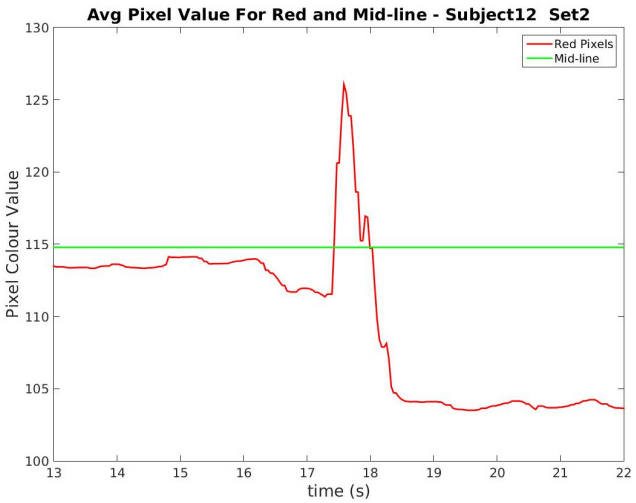


Figure 6. Graph showing the red pixel values and mid-line of the average between the largest and smallest values

Each identified significant positive gradient was represented as a positive step in the mid-line and the significant negative gradient is represented by a negative step, as seen in Figure 7. It is possible that artefacts in the red pixel graph mean a gradient which is larger than the threshold, but not

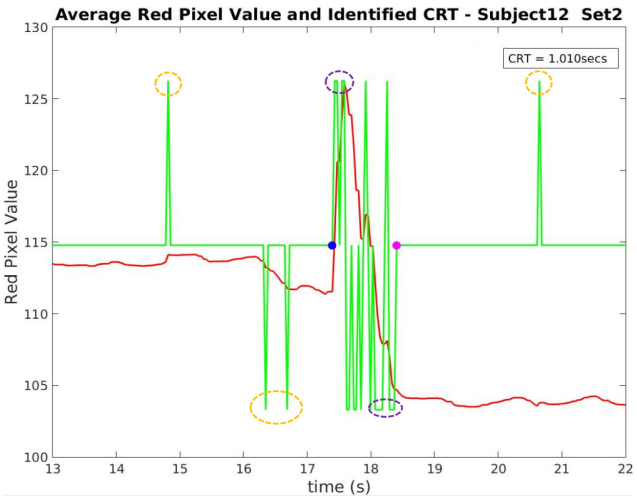


Figure 7. Graph showing the red pixel values and the identified significant gradients

of interest, is detected (illustrated by the dashed orange circles in Figure 7). In order to ensure these gradients are not considered, the gradients are analysed to identify periods where there is a series of gradient values consistently above the threshold (illustrated by the dashed purple circles in Figure 7). This enables accurate identification of the significant positive and negative gradients of interest, i.e. indicating the start and end of the CRT.

The first period of consecutive positive gradients above the threshold is identified as the start of the time period where the capillaries are refilling with blood and the last period of consecutive negative gradients below the threshold is the end of the capillary refill time period (identified by the dashed, purple circles in Figure 7). Therefore the time stamps of one frame before the first period of consecutive positive gradients and after the last period of consecutive negative gradients is identified. These are represented by the blue and magenta coloured dots respectively in Figure 7. The time difference between each instance is calculated and represents the CRT of the subject. The CRT is calculated for each of the three data sets collected for all 12 subjects.

4. Results

This section presents results for the experiments calculating the CRT for the 12 healthy human subjects of a range of skin colour, including 7 subjects from Northern Ireland, 1 from England, 1 from Central Africa, 2 from India and 2 from China. Table 1 presents the average, minimum and maximum calculated CRT in seconds using the 3 sets of video data collected for each subject. Also, the number of sets which correctly calculated the CRT as taking less than 2 seconds is stated for each subject. In some cases, for example if the subject is elderly or an infant, the CRT can be as high as 4.5 seconds. However, generally speaking the majority of people should have a CRT of no more than 2 seconds according to a medical professional and [24]. Since there were no elderly or infant subjects assessed, 2 seconds is used as the threshold to determine if subjects are healthy or in a state or shock or critical condition.

Table 1. Table outlining the calculated CRT experimental results

Subject	**Average (*s*)**	**Min (*s*)**	**Max (*s*)**	**No. Sets** $< 2secs$
1	0.976	0.909	1.082	3
2	0.739	0.551	0.842	3
3	0.869	0.681	0.995	3
4	1.117	0.976	1.222	3
5	1.421	1.085	1.877	3
6	1.715	0.759	3.554	2
7	1.001	0.940	1.121	3
8	1.081	0.875	1.264	3
9	3.772	1.091	6.983	1
10	0.988	0.908	1.121	3
11	2.362	0.978	5.019	2
12	1.111	1.010	1.309	3

As shown in Table 1 the CRT was accurately calculated and correctly determined as less than 2 seconds in 32 of the 36 ($\approx 89\%$) tested video data sets. The video data for subject 9 proved to be the most difficult from which to accurately calculate the CRT, with two of the datasets being calculated as greater than 2 seconds. One of the sets was as high as almost 7 seconds and was a particularly noisy dataset which contained numerous prolonged positive gradients. These spikes in the red pixel value could be caused by an unexpected change in ambient lighting or a shaking of the camera during recording. However, in the majority of instances the values calculated are within the expected range of 0.5-2 seconds for healthy subjects of varying skin colour, meaning the algorithm proved to be robust regardless of skin colour.

5. Conclusion and Future Work

This paper presents an algorithm capable of determining one of the vital signs of human health, namely CRT. An adult humans CRT should normally be less than 2 seconds if they are in a healthy state. The algorithm used tactile sensing data for control of the BioTAC fingertip and a camera to collect vision data which were later analysed to determine the duration of time lapsed before a subject's skin colour returned to its normal tone. The algorithm proved to be effective and robust across a range of skin tones, determining a correct measurement of CRT in 32 of the 36 subject datasets. The algorithm presented has been evaluated on a relatively small trial sample to date, therefore ethical ap-

proval will be sought to extend the subject set to include infants, elderly subjects and perhaps subjects that are not healthy to further evaluate the algorithm.

Using this algorithm for measuring CRT together with previously developed algorithms for measuring BPM and RR, it is planned for future work to equip a first responder robot with the skills necessary to assess three of a human's vital signs, namely BPM, RR and CRT, in an emergency situation. Uploading all of the collected data to a cloud based system capable of applying the respective algorithms to the data will allow for the assessment of a subject's health by a medical professional.

References

[1] J. Beckow, "The truth about capillary refill." *JEMS: a journal of emergency medical services*, vol. 30, no. 1, pp. 14–discussion, 2005. 1

[2] K. Strozik, C. Pieper, and J. Roller, "Capillary refilling time in newborn babies: normal values," *Archives of Disease in Childhood - Fetal and Neonatal Edition*, vol. 76, no. 3, pp. F193–F196, 1997. [Online]. Available: http://fn.bmj.com/content/76/3/F193.abstract 1

[3] D. King, R. Morton, and C. Bevan, "How to use capillary refill time," *Archives of Disease in Childhood - Education and Practice*, vol. 99, no. 3, pp. 111–116, 2014. [Online]. Available: http://ep.bmj.com/content/99/3/111 1

[4] A. Pamba and K. Maitland, "Capillary refill: prognostic value in kenyan children," *Archives of Disease in Childhood*, vol. 89, no. 10, pp. 950–955, 2004. [Online]. Available: http://adc.bmj.com/content/89/10/950 1

[5] J. Saavedra, G. Harris, S. Li, and L. Finberg, "Capillary refilling (skin turgor) in the assessment of dehydration," *American Journal of Diseases of Children*, vol. 145, no. 3, pp. 296–298, 1991. [Online]. Available: +http://dx.doi.org/10.1001/archpedi.1991.02160030064022 1

[6] E. Kerr, T. McGinnity, S. Coleman, and A. Shepherd, "Towards pulse detection and rhythm analysis using a biomimetic fingertip," in *2015 IEEE International Joint Conference on Neural Networks, July 12-17 2015, Killarney, Ireland*, July 2015. 1, 3

[7] E. Kerr, T. McGinnity, and S. Coleman, "Tactile sensing for assistive robotics," Ph.D. dissertation, Dissertations & Theses Gradworks, Ulster University, 2018. 1

[8] A. Fishel, "Design and use of a biomimetic tactile microvibration sensor with human-like sensitivity and its application in texture discrimination using bayesian exploration," Ph.D. dissertation, Dissertations & Theses Gradworks, University of Southern California, 2012. 1, 3

[9] W. Karlen, A. Pickard, J. Daniels, A. Kwizera, C. Ibingira, G. Dumont, and J. Ansermino, "Automated validation of capillary refill time measurements using photoplethysmogram from a portable device for effective triage in children," in *2011 IEEE Global Humanitarian Technology Conference*, Oct 2011, pp. 66–71. 2

[10] H. Otieno, E. Were, I. Ahmed, E. Charo, A. Brent, and K. Maitland, "Are bedside features of shock reproducible between different observers?" *Archives of Disease in Childhood*, vol. 89, no. 10, pp. 977–979, 2004. [Online]. Available: http://adc.bmj.com/content/89/10/977 2

[11] A. Pickard, W. Karlen, and J. Ansermino, "Capillary refill time: Is it still a useful clinical sign?" *Anesthesia & Analgesia*, vol. 113, no. 1, pp. 120–123, July 2011. [Online]. Available: https://journals.lww.com/anesthesia-analgesia/fulltext/2011/07000/Capillary_Refill_Time___Is_It_Still_a_Useful.21.aspx 2

[12] M. Gorelick, K. Shaw, and M. Baker, "Effect of ambient temperature on capillary refill in healthy children," *Pediatrics*, vol. 92, no. 5, pp. 699–702, 1993. [Online]. Available: http://pediatrics.aappublications.org/content/92/5/699 2

[13] L. Brown, N. Prasad, and T. Whitley, "Adverse lighting condition effects on the assessment of capillary refill," *The American Journal of Emergency Medicine*, vol. 12, no. 1, pp. 46–47, 1994. [Online]. Available: http://www.sciencedirect.com/science/article/pii/0735675794901961 2

[14] L. Blaxter, D. Morris, J. Crowe, C. Henry, S. Hill, D. Sharkey, H. Vyas, and B. Hayes-Gill, "An automated quasi-continuous capillary refill timing device," *Physiological Measurement*, vol. 37, no. 1, December 2015. [Online]. Available: http://eprints.nottingham.ac.uk/35137/ 2

[15] E. Kviesis-Kipge, E. Curkste, J. Spigulis, and D. Gardovska, "Optical studies of the capillary refill kinetics in fingertips," in *World Congress on Medical Physics and Biomedical Engineering, September 7 - 12, 2009, Munich, Germany*, O. Dössel and W. Schlegel, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 377–379. 2

[16] I. Shavit, R. Brant, C. Nijssen-Jordan, R. Galbraith, and D. Johnson, "A novel imaging technique to measure capillary-refill time: improving diagnostic accuracy for dehydration in young children with gastroenteritis," *Pediatrics*, vol. 118, no. 6, pp. 2402–2408, Dec 2006. 2

[17] Syntouch. (2013) The syntouch website. [Online]. Available: http://www.syntouchllc.com/Products/BioTac/ 2, 3

[18] C.-H. Lin, T. Erickson, J. Fishel, N. Wettels, and G. Loeb, "Signal processing and fabrication of a biomimetic tactile sensor array with thermal, force and microvibration modalities." in *ROBIO*. IEEE, 2009, pp. 129–134. [Online]. Available: http://dblp.uni-trier.de/db/conf/robio/robio2009.html#LinEFWL09 2, 3

[19] E. Kerr, T. McGinnity, and S. Coleman, "Material classification based on thermal properties - a robot and human evaluation," in *2013 IEEE International Conference on Robotics and Biomimetics, December 12-14 2013, Shenzhen, China*, Dec 2013, pp. 1048–1053. 2, 3

[20] Shadow Robot Company. (2017) Shadow dexterous hand. [Online]. Available: http://www.shadowrobot.com/products/dexterous-hand/ 3

[21] ATi. (2017) Ati f/t sensor: Nano17. [Online]. Available: http://www.ati-ia.com/products/ft/ft_models.aspx?id=Nano17 4

[22] FFmpeg Developers, "ffmpeg tool (version be1d324)," 2016. [Online]. Available: http://ffmpeg.org/ 4

[23] MATLAB, *version 8.5.0.197613 (R2015a)*. Natick, Massachusetts: The MathWorks Inc., R2015. 4

[24] Royal College of Physicians of London, *National Early Warning Score (NEWS): Standardising the Assessment of Acute-Illness Severity in the NHS*. Royal College of Physicians of London, 2012. [Online]. Available: https://books.google.co.uk/books?id=5sVdMwEACAAJ 6